Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Particle Physics Applications with High Energy Beams

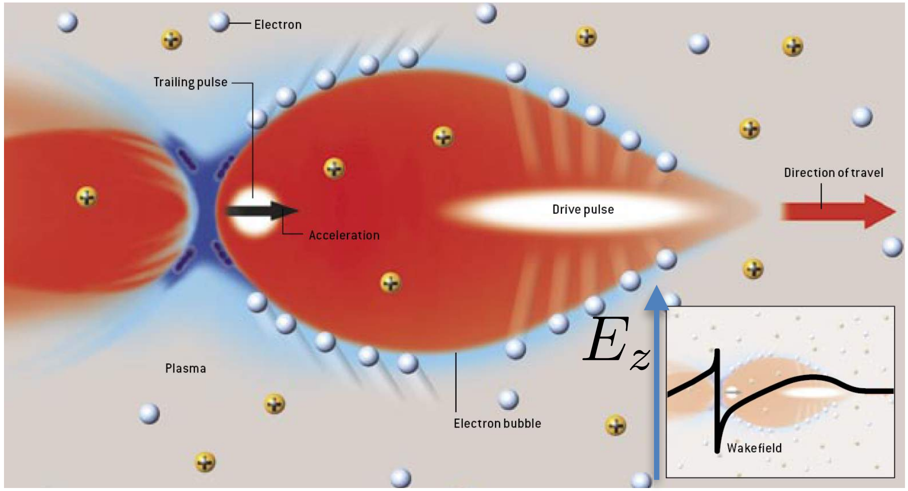
Allen Caldwell
Max-Planck-Institut für Physik

1. Technology - Plasma wakefield acceleration
    A. Laser wakefield acceleration
    B. Beam driven wakefield acceleration
2. Physics potential of HE beams
    A. Beam Dump
    B. Fixed Target
    C. Collider applications
    D. Other applications

Plasma as Accelerator Medium

An intense **particle beam**, or intense **laser beam**, can be used to drive the plasma electrons into oscillation.

$$\omega_p^2 = \frac{4\pi n_p e^2}{m}$$



C. Joshi, UCLA

For a relativistic driver: $\lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1 \cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$

Ideas of **~100 GV/m** electric fields in plasma, using 10^{18} W/cm^2 lasers: 1979 **T.Tajima and J.M.Dawson** (UCLA), Laser Electron Accelerator, Phys. Rev. Lett. 43, 267–270 (1979).
Using partice beams as drivers: **P. Chen et al**. Phys. Rev. Lett. 54, 693–696 (1985)

Energy Budget:

Witness:

10^{10} particles @ 1 TeV ≈ few kJ

Drivers:

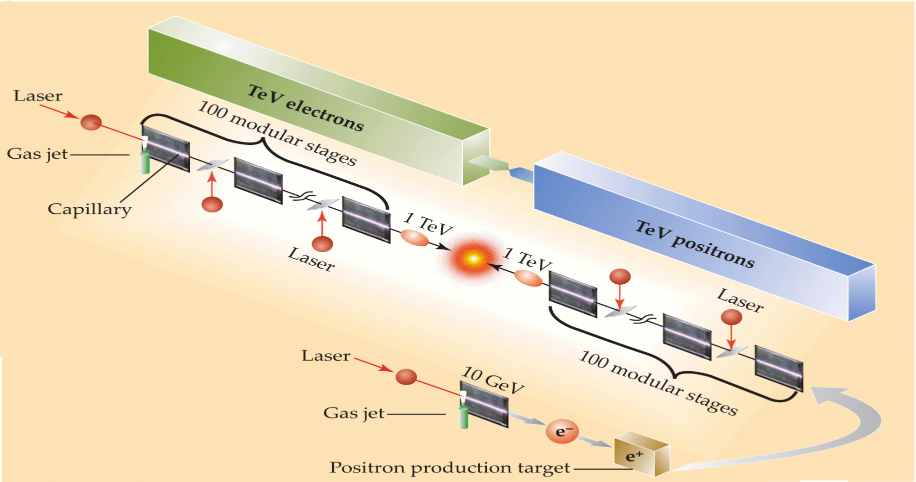
PW lasers today, ~40 J/Pulse

FACET (e beam, SLAC), 30J/bunch

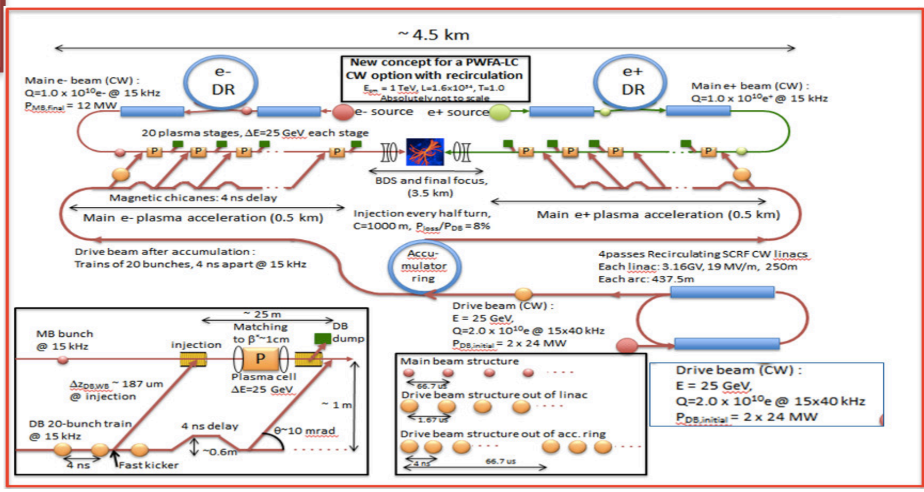
SPS@CERN 20kJ/bunch

LHC@CERN 300 kJ/bunch

Staging Concepts



Leemans & Esarey, Phys. Today ***62 #3*** *(2009)*



E. Adli et al. arXiv:1308.1145,2013

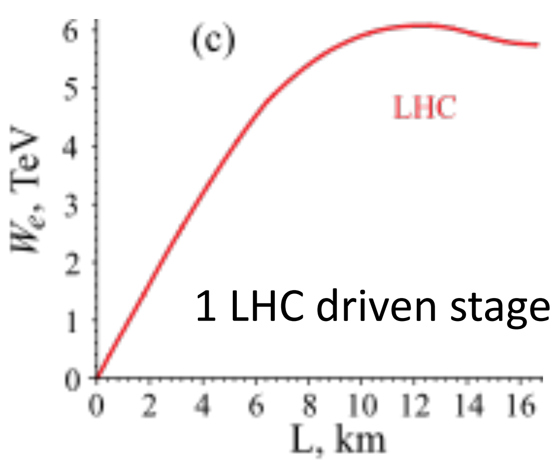
Dephasing

$$\delta \approx \frac{\pi L}{\lambda_p}\frac{1}{\gamma^2}$$

SPS: ~100m,

LHC: ~few km

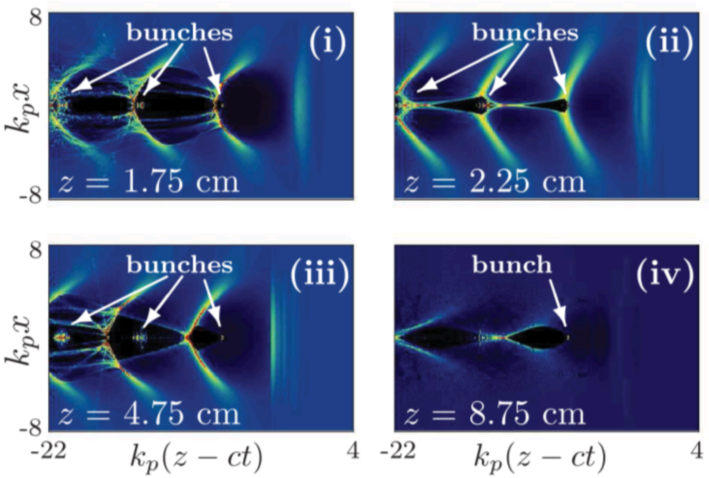
FCC: ~ ∞

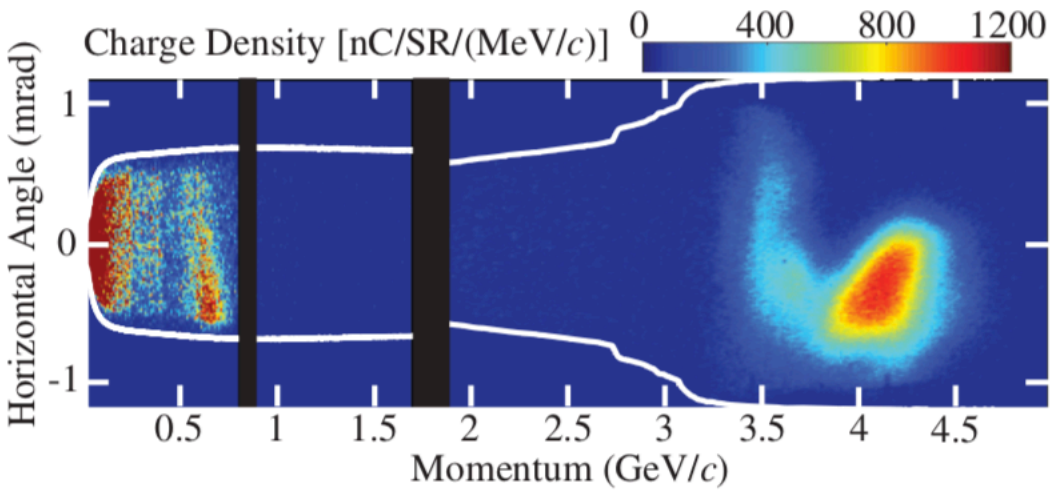


1 LHC driven stage

A. Caldwell and K. V. Lotov, Phys. Plasmas **18,** 103101 (2011)

LWFA State-of-the-Art





PIC simulation of electron acceleration: 16J BELLA laser focused at the entrance of a 9 cm channel. Plasma density $n_p = 7 \cdot 10^{17} \mathrm{cm}^{-3}$

W. P. Leemans et al., PRL **113,** 245002 (2014)

	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

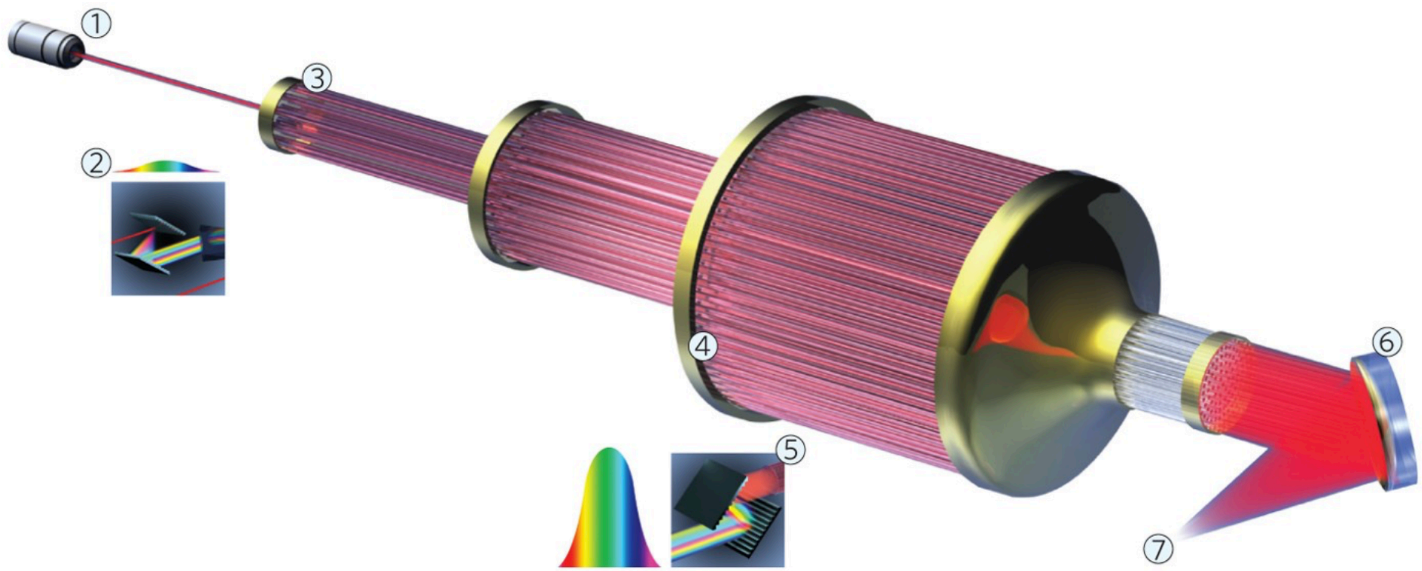
First results on external electron bunch injection, two-stage acceleration (S. Steinke et al., Nature **530**, 190 (2016))

See also X. Wang et al., Nat. Comm. 2013, H.T.Kim et al., Sc. Reports 2017, C. Clayton et al., PRL 2010,

The future is fibre accelerators

Gerard Mourou, Bill Brocklesby, Toshiki Tajima and Jens Limpert

Could massive arrays of thousands of fibre lasers be the driving force behind next-generation particle accelerators? The International Coherent Amplification Network project believes so and is currently performing a feasibility study.



PHIL SAUNDERS

An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).

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Optics EXPRESS

Coherent beam combining of seven fiber chirped-pulse amplifiers using an interferometric phase measurement

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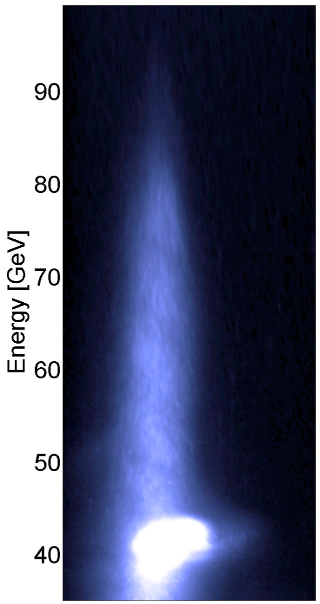
5. Conclusion and outlook

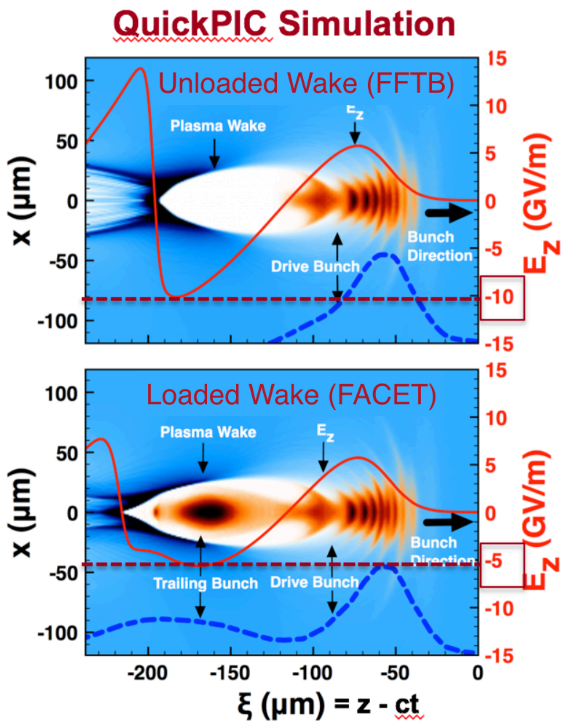
In summary, we demonstrated the first coherent combination of seven fiber amplifiers using an interferometric phase measurement method. Operating in linear regime, a combination efficiency of 48% has been achieved, with a residual phase error between two fibers as low as $\lambda/55$ RMS. The laser system delivers 71 W average power at a repetition rate of 55 MHz and with a pulse duration of 216 fs. In nonlinear regime, the same residual phase error and a slightly reduced combining efficiency of 45% were obtained. These very promising results show that our laser system is well adapted for the coherent combination of high power active fibers in tiled aperture configuration. Therefore, and since an upscaled version of our system will rely on the same scientific and technical principles, the implementation of 54 additional fibers and the operation of this final 61 fiber system will be demonstrated as a next step.

PWFA State-of-the-Art

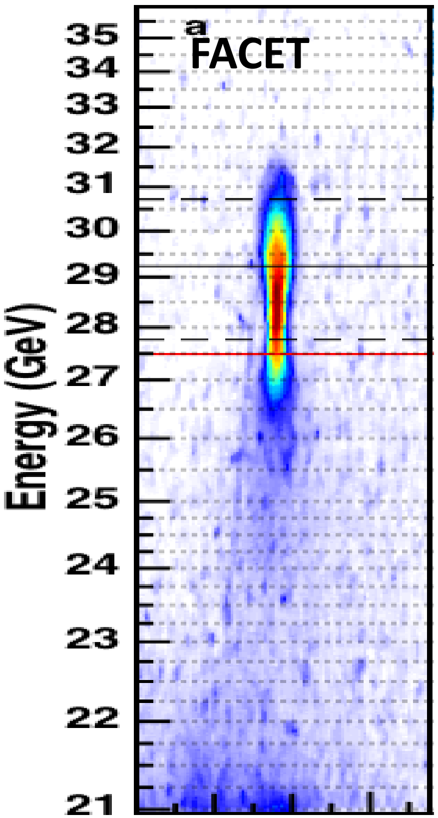
43 GeV energy gain
FFTB



SLAC



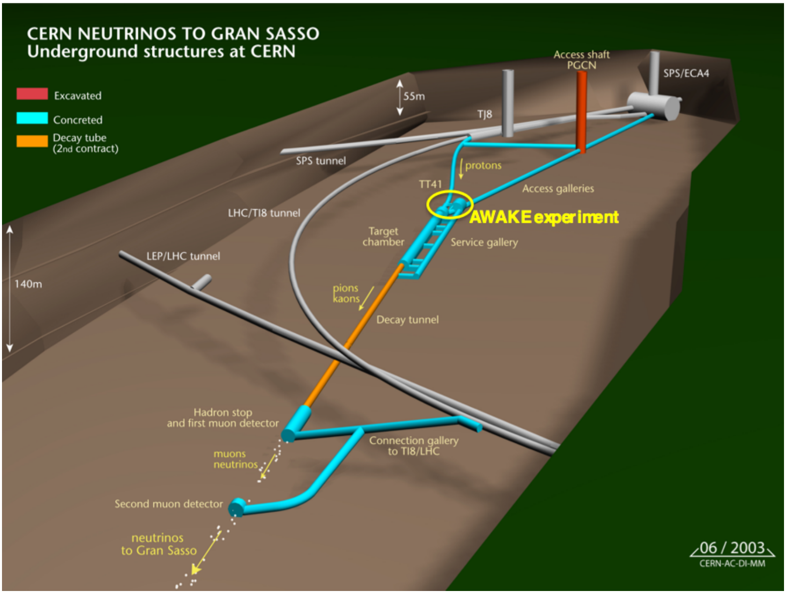
9 GeV energy gain,
efficiency 20%



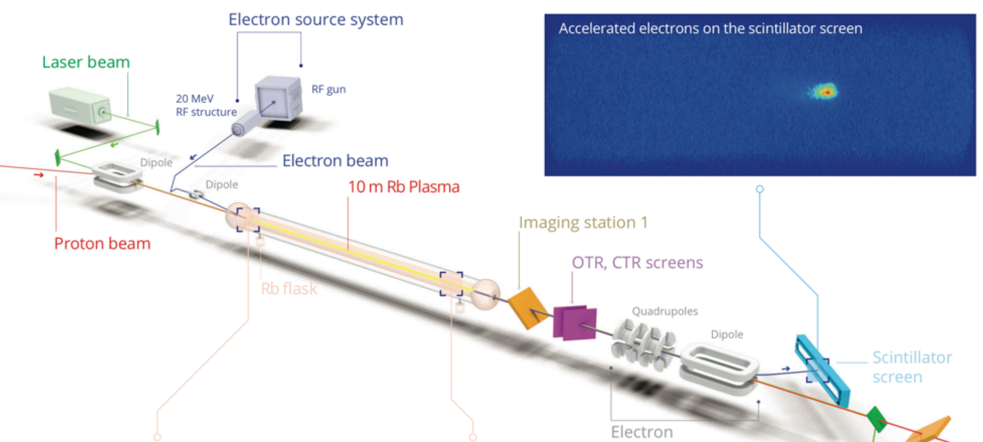
Blumenfeld et al., Nature **445**, 741 (2007), Muggli et al., New Jour. of Phys **12** , 045022 (2010) , Litos et al., Nature **515,** 92 (2014)

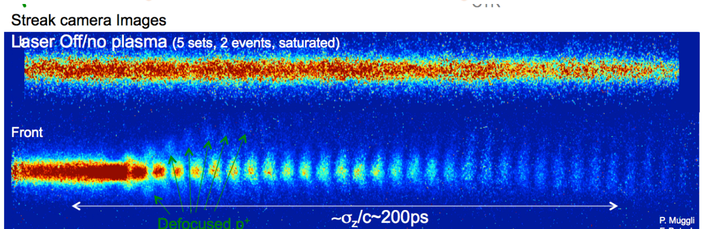
Narrow energy spread acceleration with high-efficiency has been demonstrated. Next decade will focus on simultaneously preserving beam emittance and addressing acceleration of positrons. (Courtesy: M. Hogan, SLAC)

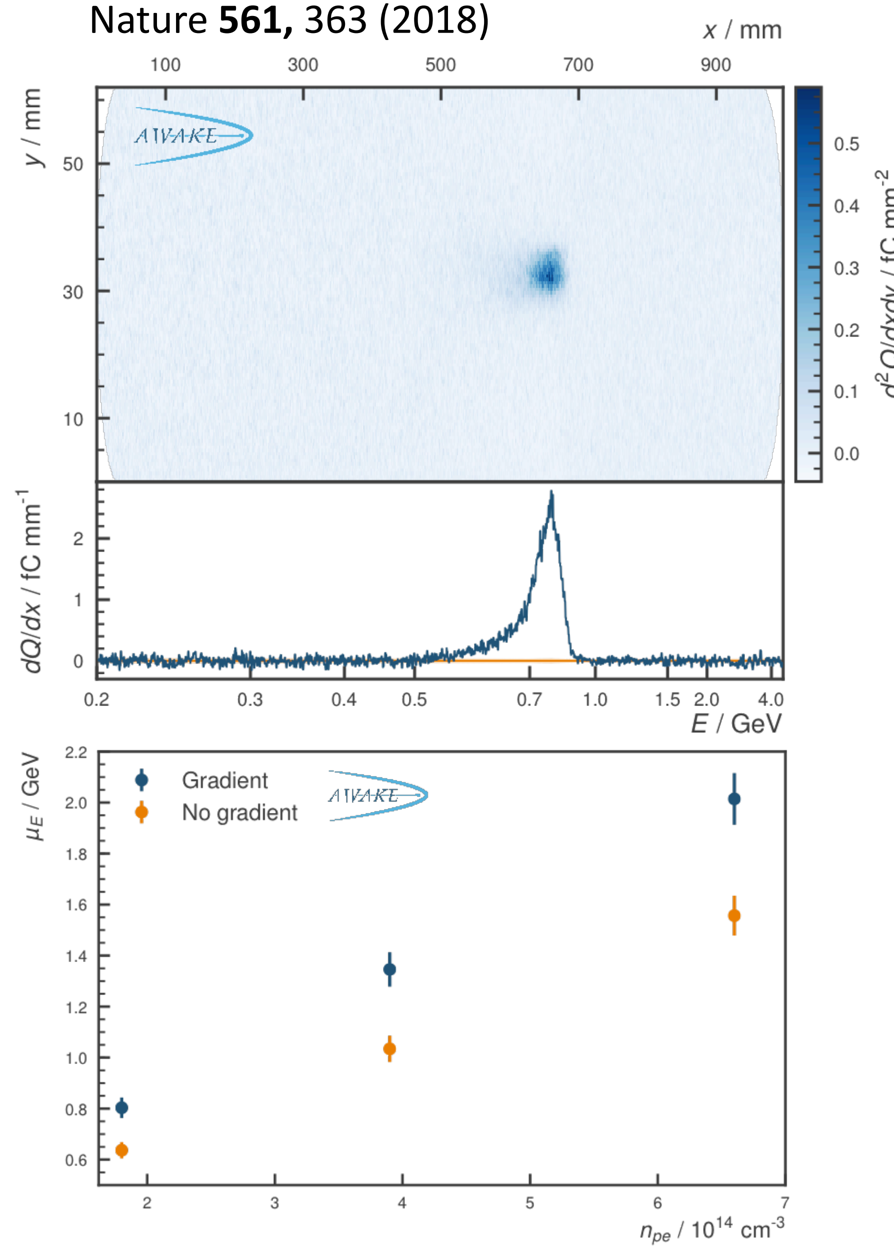
AWAKE



E. Adli et al., AWAKE Collaboration, Nature **561,** 363 (2018)





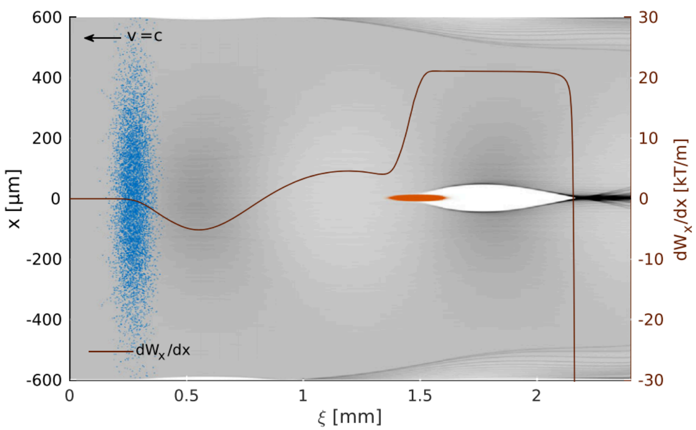


Seeded self-modulation robust !

AWAKE Run 2

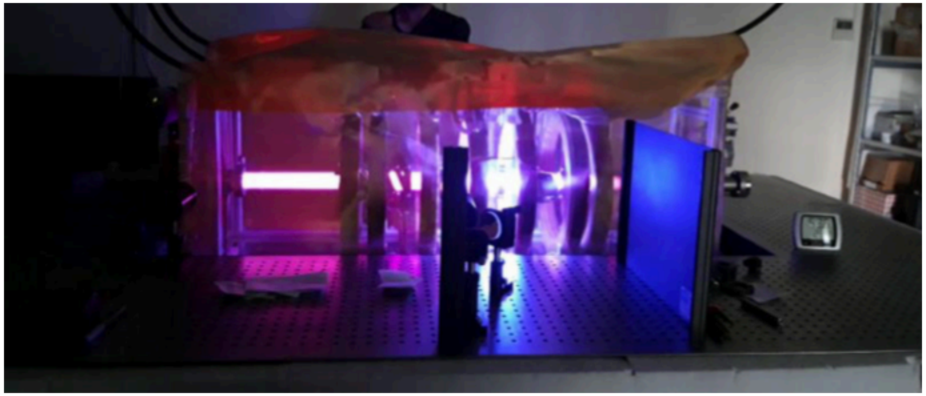
Goals:
stable acceleration of bunch of electrons with high gradients over long distances
'good' electron bunch emittance at plasma exit
Be prepared to start particle physics experiment after Run 2

Beam loading to improve emittance



V.K. Berglyd Olsen, E. Adli and P. Muggli
Phys. Rev. Accel. Beams

Density needed for AWAKE achieved at the IPP in Greifswald. Study uniformity, scalability at CERN. New laboratory.



LHC as driver

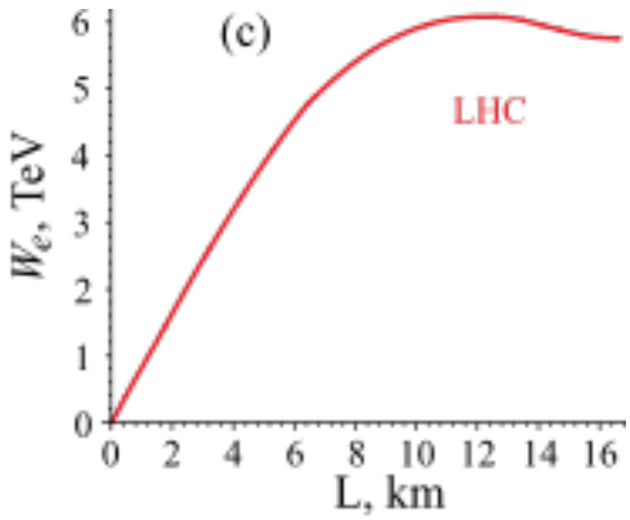
From simulations of seeded, self-modulated proton beams:

Energy reach using the LHC <= 6 TeV

Physics of Plasmas **18**, 103101 (2011);

A. Caldwell and K. V. Lotov

Here: 1.15 10^{11} protons assumed. Gradients could be larger



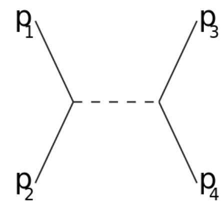
Number of electrons/proton estimated ~5% for SPS. Not yet studied for the LHC

Particle Physics possibilities

looking for good ideas ….

General Considerations

s-channel cross sections scale as $\sigma \propto \frac{1}{s}$



$$n_{\text{fixed}} \implies \mathscr{L} \propto s$$

Power!

very difficult to see today how high luminosity and high energy and affordability can be achieved in a linear collider:

LWFA - need high power AND high energy AND high efficiency laser …

PWFA - electron driver will need many stages, emittance preservation, positrons (for s-channel), …

PWFA - proton driver. With LHC, many TeV foreseeable but low rep rate, dedicated short cycling time proton accelerator?

As intermediate step, think what physics we can get from single high energy beams or low luminosity collider.

Questions

If we could provide a 5 TeV/electron bunch, with 10^{10} electrons/bunch on average 1/s - who's interested?

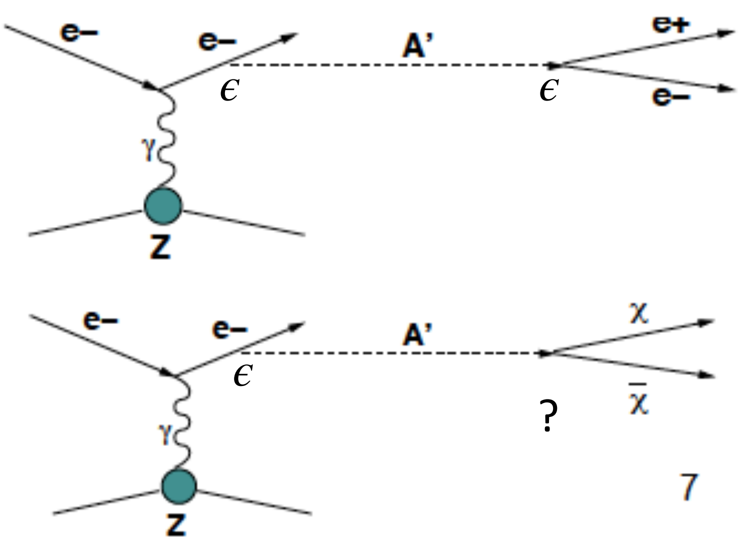
If we could provide 1 PeV/electrons with 10^{9}electrons/bunch on average 1/1000s - who's interested?

Energies are of course available in cosmic rays, but not in the lab. What can be studied in a lab environment? If the cost is reasonable, should go on an exploratory mission.

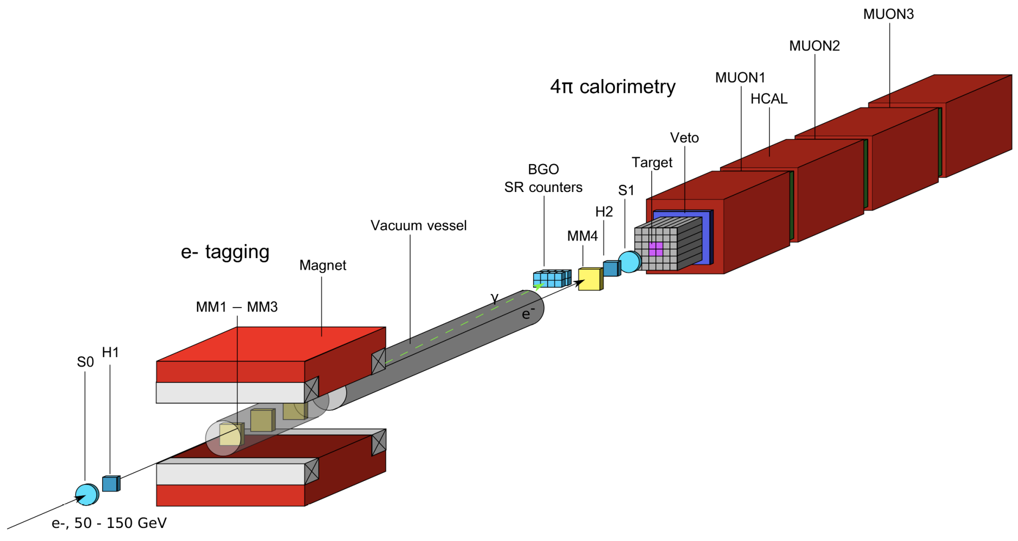
Need many crazy ideas - one of them may turn out not to be so crazy.

Beam Dump

Example: Dark photon search a la NA64. Currently: secondary electron beam from SPS. Provides 10^6 electrons/s, E=100 GeV

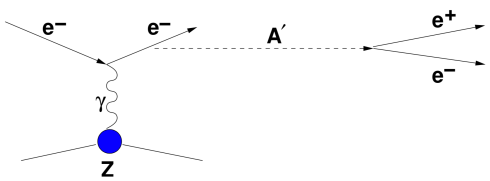


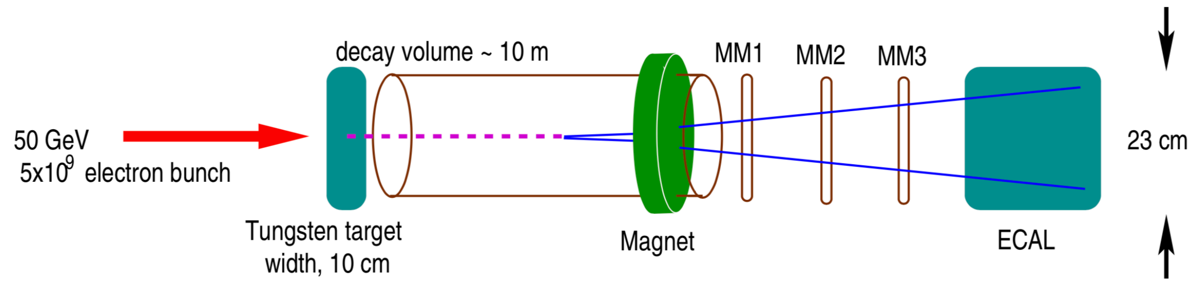
Decaying dark photons: into visible or invisible mode. For invisible mode - need to track individual electrons. How to do this in a bunched beam?



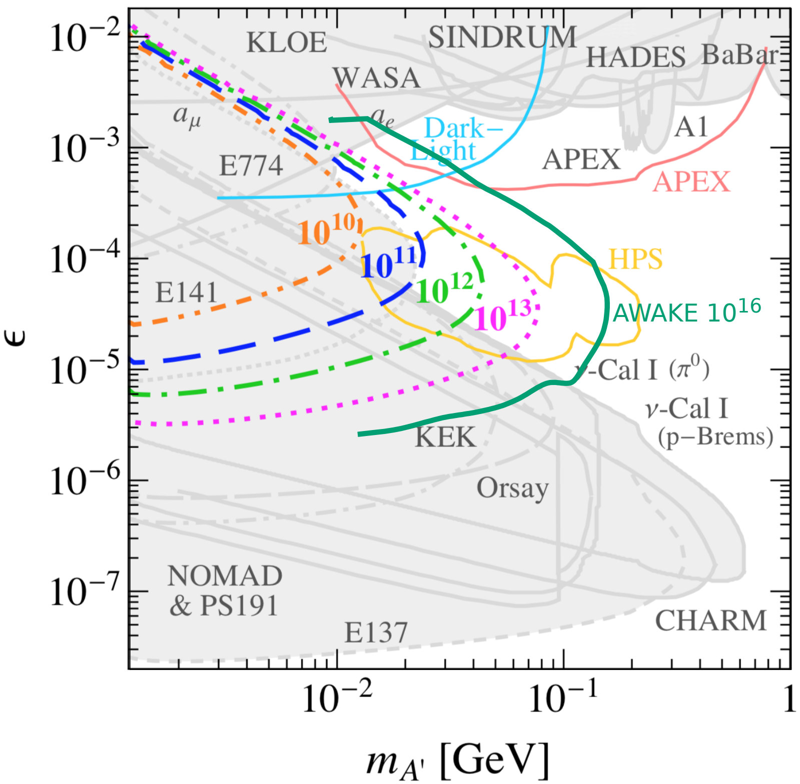
See e.g.: https://arxiv.org/pdf/2005.01515.pdf. 'The Physics of the Dark Photon'

Beam Dump

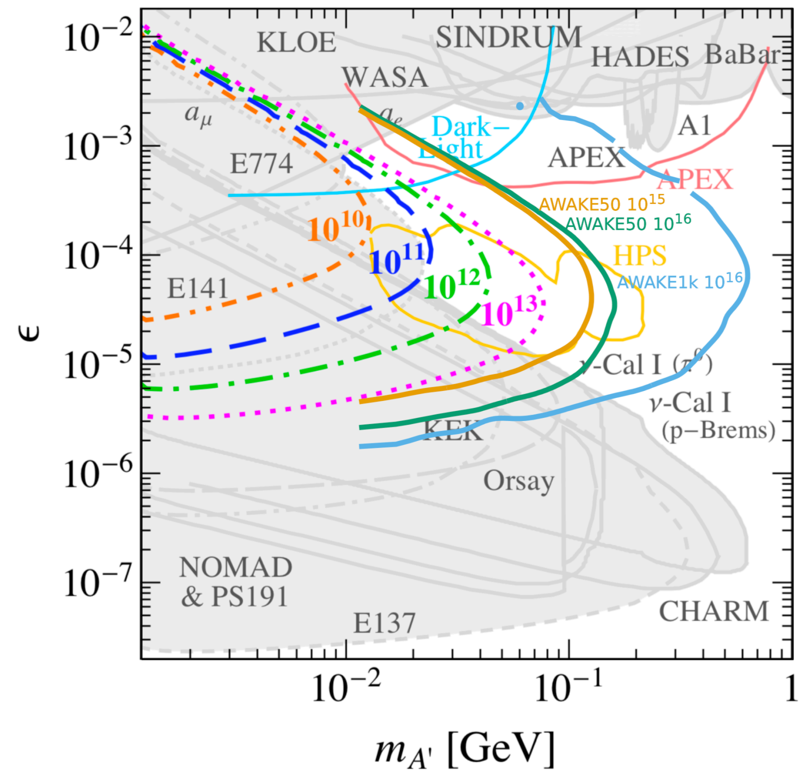




Expectation for 3 month run



Expectation for 10^{16} 1 TeV electrons



A. Hartin, UCL

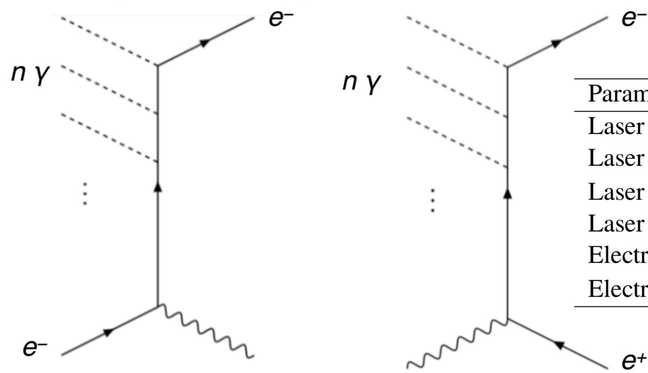
Strong Field QED

Idea: probe QED in the strong field regime (Schwinger critical field ~10^{18} /m). Expect to see nonlinear effects in controlled laboratory environment.

high power laser

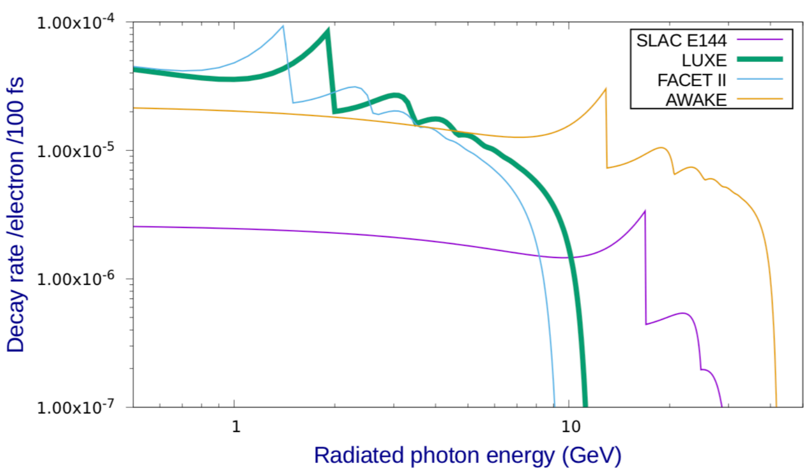
e.g.,

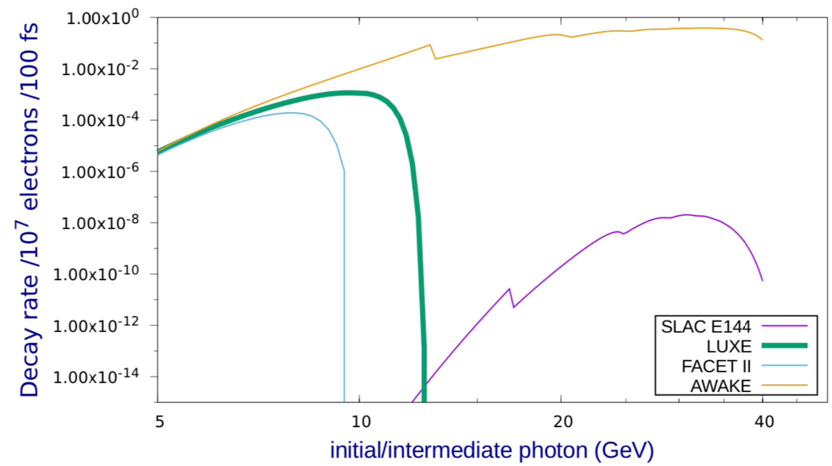
$e^- + n\gamma \rightarrow e^- + \gamma$ $\quad\quad$ $\gamma + n\gamma \rightarrow e^+ + e^-$



Parameter	E144	LUXE	FACET II	AWAKE
Laser wavelength (nm)	527/1053	527/1053	527/800/1053	527
Laser energy (J)	2	2	1	1
Laser transverse size (μm^2)	50	100	64	64
Laser pulse length (ps)	1.88	0.05	0.04	0.04
Electron energy (GeV)	46.6	17.5	15	50
Electrons per bunch	5×10^9	6×10^9	5×10^9	5×10^9

high energy electron beam





higher energy beams would be a great benefit

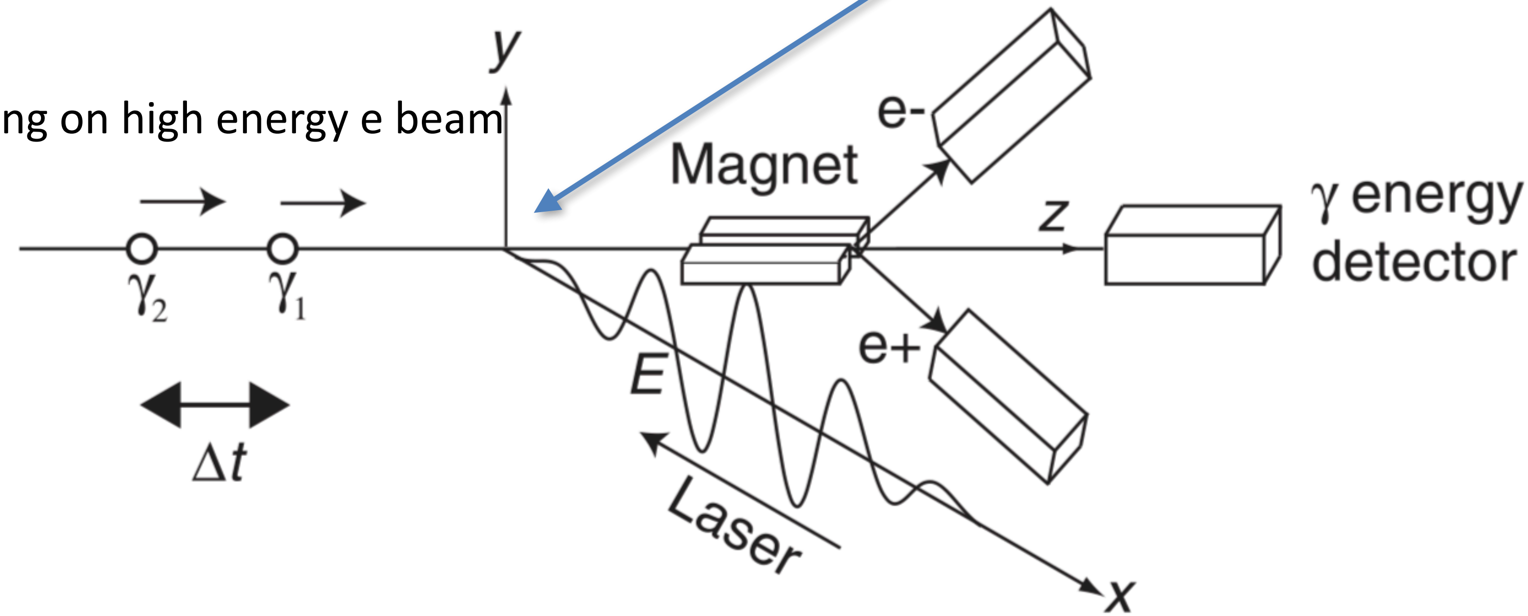
T. Tajima, M. Kando and M. Teshima, Prog. Theor. Phys. 125, 617 (2011).

Feeling the Texture of Vacuum

— *Laser Acceleration toward PeV* —

Schwinger pair creation

γ from backscattering on high energy e beam



the ability to reach PeV and to measure the fs time resolution of PeV γ photons can provide valuable data if and how gamma photons still obey the premise of relativity or the vacuum texture begins to alter such fundamentals. The only method currently available to look at this problem may be to study astrophysical data of the primordial gamma ray bursts (GRBs), which are compared with the presently suggested approach.

See also: Laboratory bounds on electron Lorentz violation

Brett Altschul

Phys. Rev. D **82**, 016002 – Published 9 July 2010

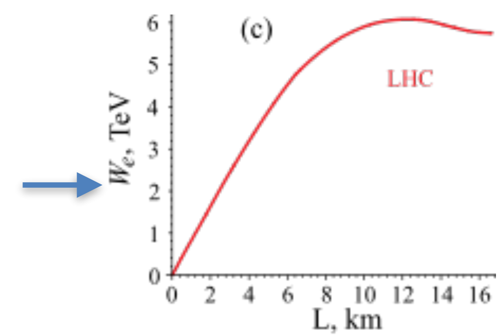
Fixed Target

Using LHC as driver, AWAKE style acceleration could reach energy regime that is comparable to the planned EIC at BNL in a fixed target mode.

Advantage: luminosity achieved via the target
Disadvantage: very forward geometry for experiment. Exclusive states may be difficult to reconstruct. Pile-up if have `thick' target.

Has not been studied … some part of the EIC program could be covered … to be investigated

Electron beam polarization maintained in blowout regime (J. Vieira et al., PRST-AB **14**, 071303(2011)
Needs investigation for AWAKE scheme



$$E_{\mathrm{CM}} = \sqrt{2M_P E_e} = 14 - 110\ \mathrm{GeV}$$

for E_e=100-6000 GeV   LHC Driver

Compass: ~20 GeV
EIC: 15-140 GeV

Prospects for a very high energy eP and eA collider

June 1,2 2017
Max Planck Institute for Physics

Registration		Auditorium, MPI Meeting rooms	09:00 - 09:15
Introduction to Workshop	Allen CALDWELL	Auditorium, MPI Meeting rooms	09:15 - 09:45
Status of AWAKE	Prof. Patric Muggli MUGGLI	Auditorium, MPI Meeting rooms	09:45 - 10:15
Introduction to VHEeP	Prof. Matthew WING	Auditorium, MPI Meeting rooms	10:15 - 10:45
Coffee		Auditorium, MPI Meeting rooms	10:45 - 11:15
The theory of small-x physics	Prof. Al MUELLER	Auditorium, MPI Meeting rooms	11:15 - 12:15
High energy cross-sections and classicalization	Prof. Gia DVALI	Auditorium, MPI Meeting rooms	12:15 - 13:00
Lunch		Auditorium, MPI Meeting rooms	13:00 - 14:00

Applying AdS/CFT to very low x physics	Prof. Johanna ERDMENGER	Auditorium, MPI Meeting rooms	14:00 - 14:45
Low x synergy between DIS and ultrahigh energy neutrinos	Prof. Anna STASTO	Auditorium, MPI Meeting rooms	14:45 - 15:30
Formation zone physics	leo STODOLSKY	Auditorium, MPI Meeting rooms	15:30 - 16:00
Coffee		Auditorium, MPI Meeting rooms	16:00 - 16:30
Symposium celebrating Leo Stodolsky's 80th birthday		Auditorium, MPI Meeting rooms	16:30 - 18:00
Reception		Auditorium, MPI Meeting rooms	18:00 - 19:15
Dinner			

Small-x physics in ep-scattering: thoughts on results from HERA and future aspects	Prof. Jochen BARTELS	Auditorium, MPI Meeting rooms	09:00 - 09:45
BKFL and dipoles	Dr. Henri KOWALSKI	Auditorium, MPI Meeting rooms	09:45 - 10:15
Color dipole at small x	Prof. Dieter SCHILDKNECHT	Auditorium, MPI Meeting rooms	10:15 - 10:45
Coffee		Auditorium, MPI Meeting rooms	10:45 - 11:15
eA physics at very high energies	Mrs. Heikki MÄNTYSAARI	Auditorium, MPI Meeting rooms	11:15 - 12:00
Polarised eP and eA physics	Dr. Elke ASCHENAUER	Auditorium, MPI Meeting rooms	12:00 - 12:45
Lunch		Auditorium, MPI Meeting rooms	12:45 - 13:45

What the HERA data tell us about low-x physics	Dr. Volodymyr MYRONENKO	Auditorium, MPI Meeting rooms	13:45 - 14:30
New results for VHEeP	Mr. Fearghus KEEBLE	Auditorium, MPI Meeting rooms	14:30 - 15:00
Simulation of high energy ep / eA collisions	Dr. Simon PLAETZER	Auditorium, MPI Meeting rooms	15:00 - 15:45
Close out	Allen CALDWELL et al.	Auditorium, MPI Meeting rooms	15:45 - 16:00

Mini-workshop on QCD and Gravity
December 12,13
Max Planck Institute for Physics

2018

Wednesday, December 12

14:15-15:15	Raju Venugopalan	'A many-body theory of QCD in the Regge limit'
15:30-16:00	Eran Palti	'News on Swampland'
16:00-16:30	Stephan Stieberger	'QCD meets Gravity'
16:30-17:00	Johanna Erdmenger	'AdS/CFT and very small x'
17:00-17:30	Angnis Schmidt-May	'News from bimetric gravity'
17:30-18:30	Discussion time	
19:00-	Dinner somewhere	

Thursday, December 13

9:00-10:00	Gia Dvali et al	'Proof of the Axion?'
10:00-10:30	Discussion time	
10:30-11:00	Henri Kowalski	'BFKL analysis of HERA data'
11:00-11:30	Agustin Sabio Vera	'The Regge limit in QCD, SUSY and gravity'
12:00-14:00	lunch and discussion	

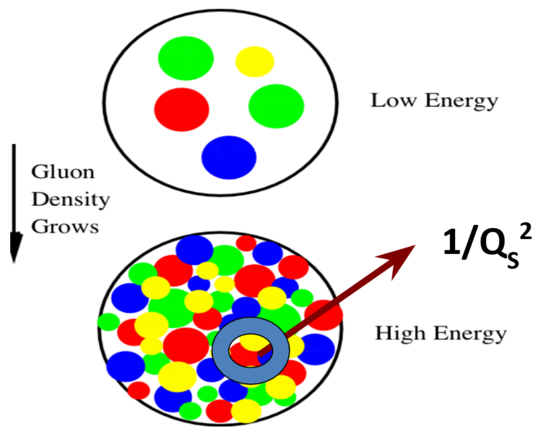
2 workshops to discuss novel physics with very high energy eP/eA collider.

Second - focus on relation between QCD and gravity.

From the Workshop

R. Venugopalan, Mini-workshop on QCD and Gravity
December 12,13 Max Planck Institute for Physics

The boosted proton viewed head-on

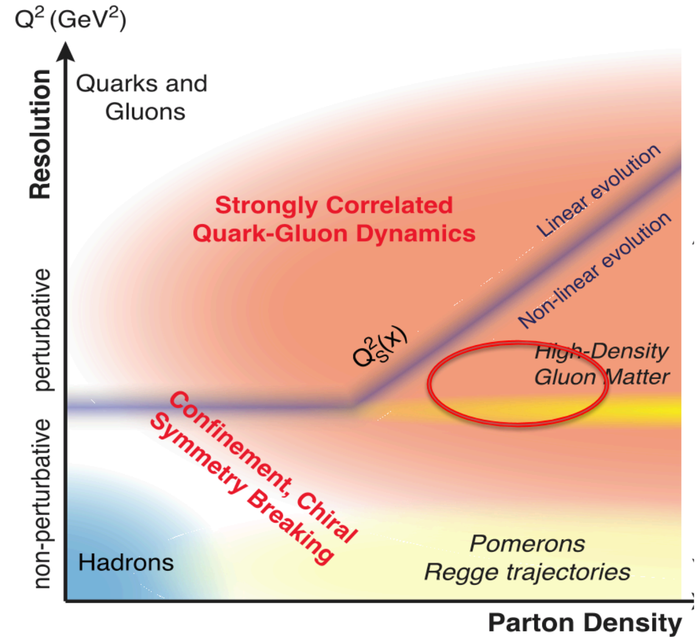


When occupancies become large ~ $1/\alpha_S$, gluons resist further close packing by recombining and screening their color charges -- leading to gluon saturation

Emergent semi-hard scale dynamical scale $Q_S(x) >> \Lambda_{QCD}$

Asymptotic freedom! $\alpha_S(Q_S) << 1$ provides weak coupling window into infrared

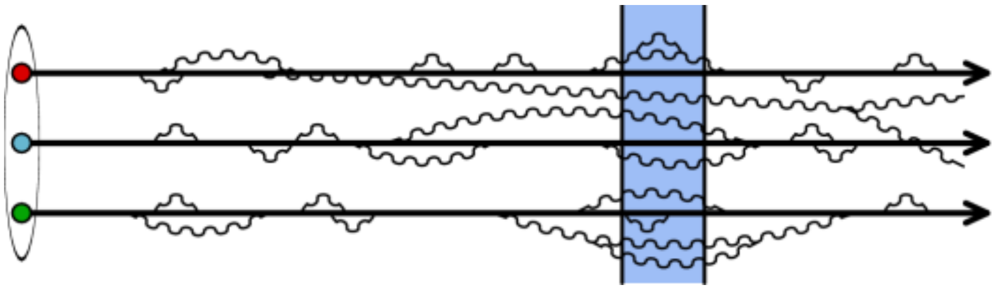
Saturation in the QCD landscape



From the physics we know - these are the strongest fields that can be achieved in nature

New: perturbative approach to infrared physics! Relevant equations very similar to fundamental statistical mechanics equations. Strong overlap with quantum description of black holes.

At high energy, see short-lived fluctuations due to time dilation



Courtesy: R. Venugopalan

Markovian process leads to power law growth of gluon distribution at small x

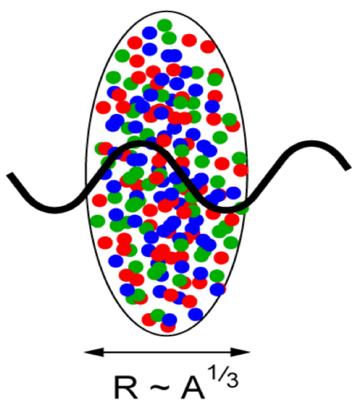
Violates Froissart bound asymptotically

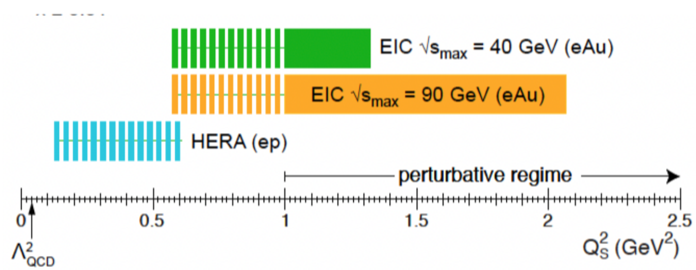
A fascinating equilibrium of splitting and recombination should eventually result. It is a considerable theoretical challenge to calculate this equilibrium in detail...

F. Wilczek, Nature (1999)

"oomph factor" from Nuclei

$Q_S^{\,2} \sim A^{1/3}$ since "wee" gluons couple coherently for $x << A^{-1/3}$





VHEeP

with VHEeP and eA, we will be in a region where the saturation scale is well into the perturbative region. Allows detailed probing of this new physics: high density & weak coupling !

QCD and Gravity: more than math ?

Consider: the visible mass is largely due to baryons. The mass of baryons is largely due to QCD (not the Higgs mechanism). Gravity couples to mass/energy ....

S. Stieberger, Mini-workshop on QCD and Gravity December 12,13 Max Planck Institute for Physics

Can gravity be described by YM-theory ?

do we see some generic or unifying structures in scattering amplitudes?

G : spin 2 $\qquad\qquad$ γ : spin 1

graviton as composite particle ?

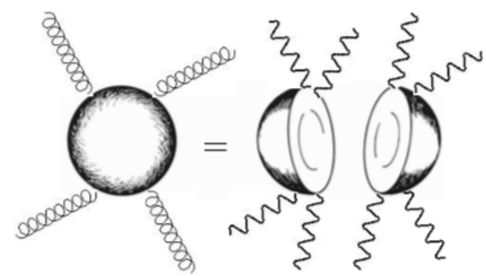
Alert: graviton cannot be a composite particle in a relativistic quantum field theory (Weinberg, Witten)

proof relies on the construction of a conserved and Lorentz-covariant stress tensor

$$T^{\mu\nu}(x) = (-g)^{-1/2} \frac{\partial}{\partial g_{\mu\nu}(x)} S[g]$$

theorem holds for any known renormalizable field-theory, e.g. QCD

However there are many ways out:
massive gravity, conformal field theory, string theory, ...

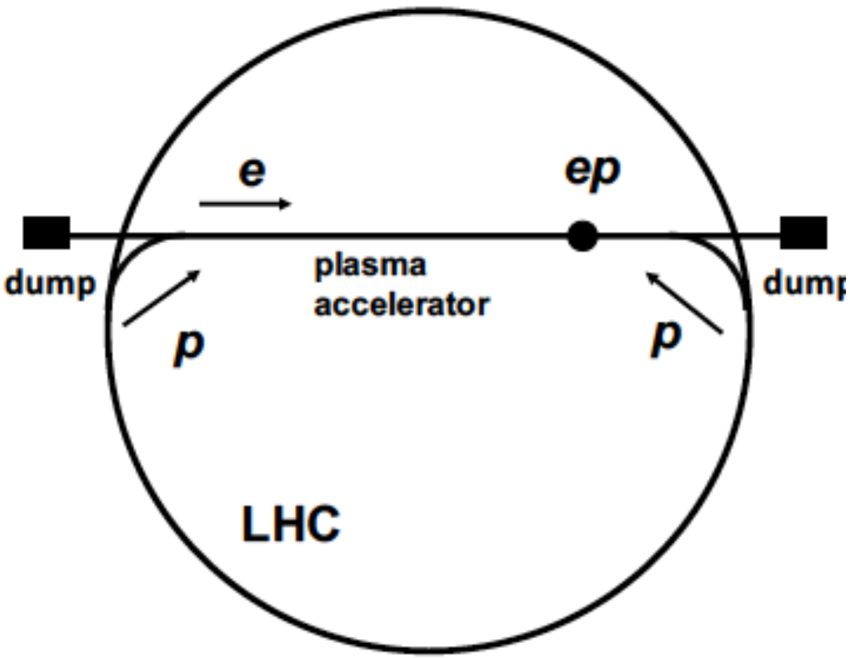


Concluding remarks

- growing set of **interconnections** between open & closed amplitudes with gauge theory and supergravity amplitudes
- indication for the existence of some **gauge structure** in **quantum gravity**

VHEeP

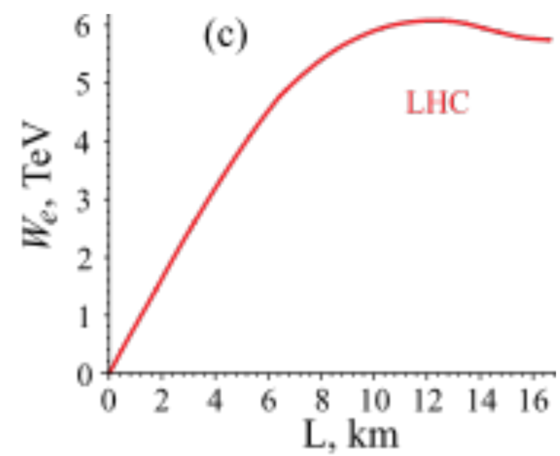
(Very High Energy electron-Proton collider)



One proton beam used for electron acceleration to then collide with one bunch from other proton beam

Luminosity ~ $10^{28} – 10^{29}$ cm^{-2} s^{-1} gives ~ 1 pb−1 per year.

Electron energy from wakefield acceleration by LHC bunch



A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

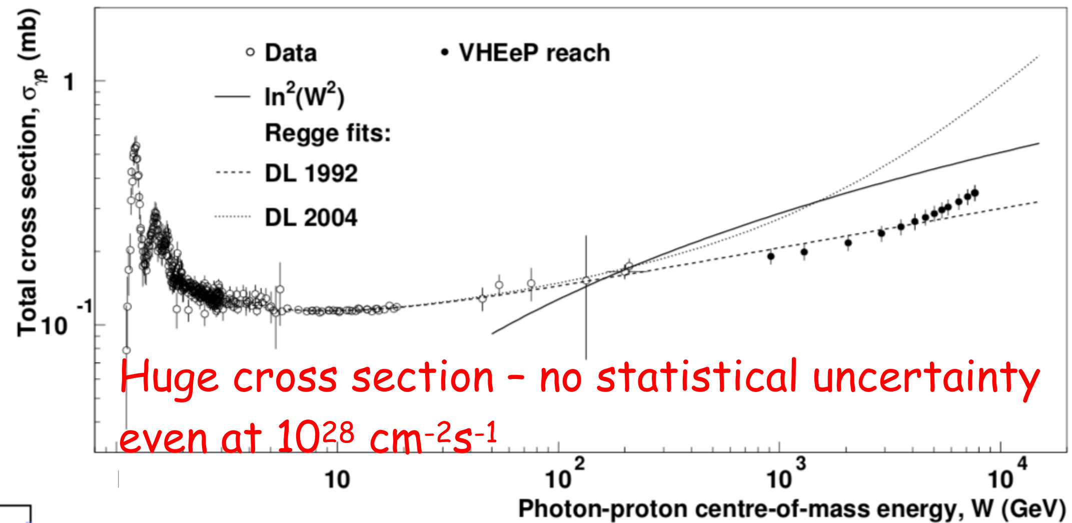
Choose E_e = 3 TeV as a baseline for a new collider with E_p = 7 TeV yields $\sqrt{s}$ = 9 TeV. Can vary.

- Center-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives

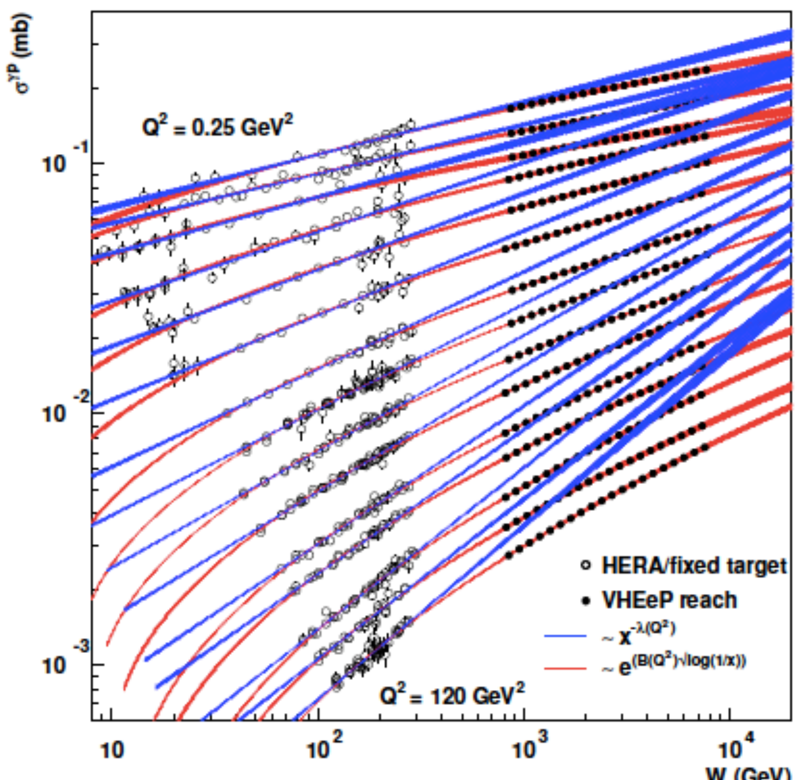
VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Colliding 3 TeV electrons with LHC Protons

Total photoproduction cross section – energy dependence ?
See approach to Froissart bound ?
Impact on cosmic ray physics

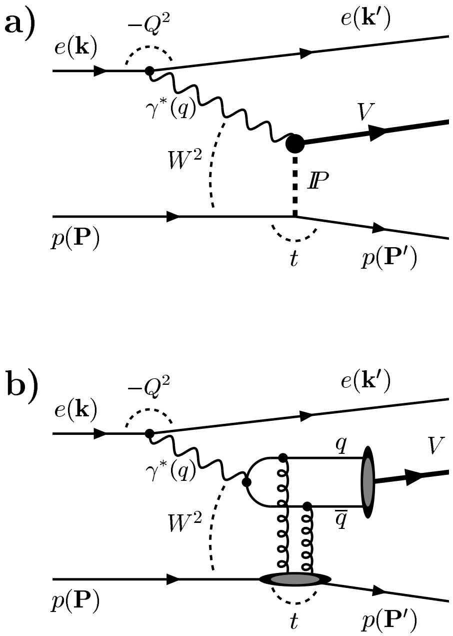


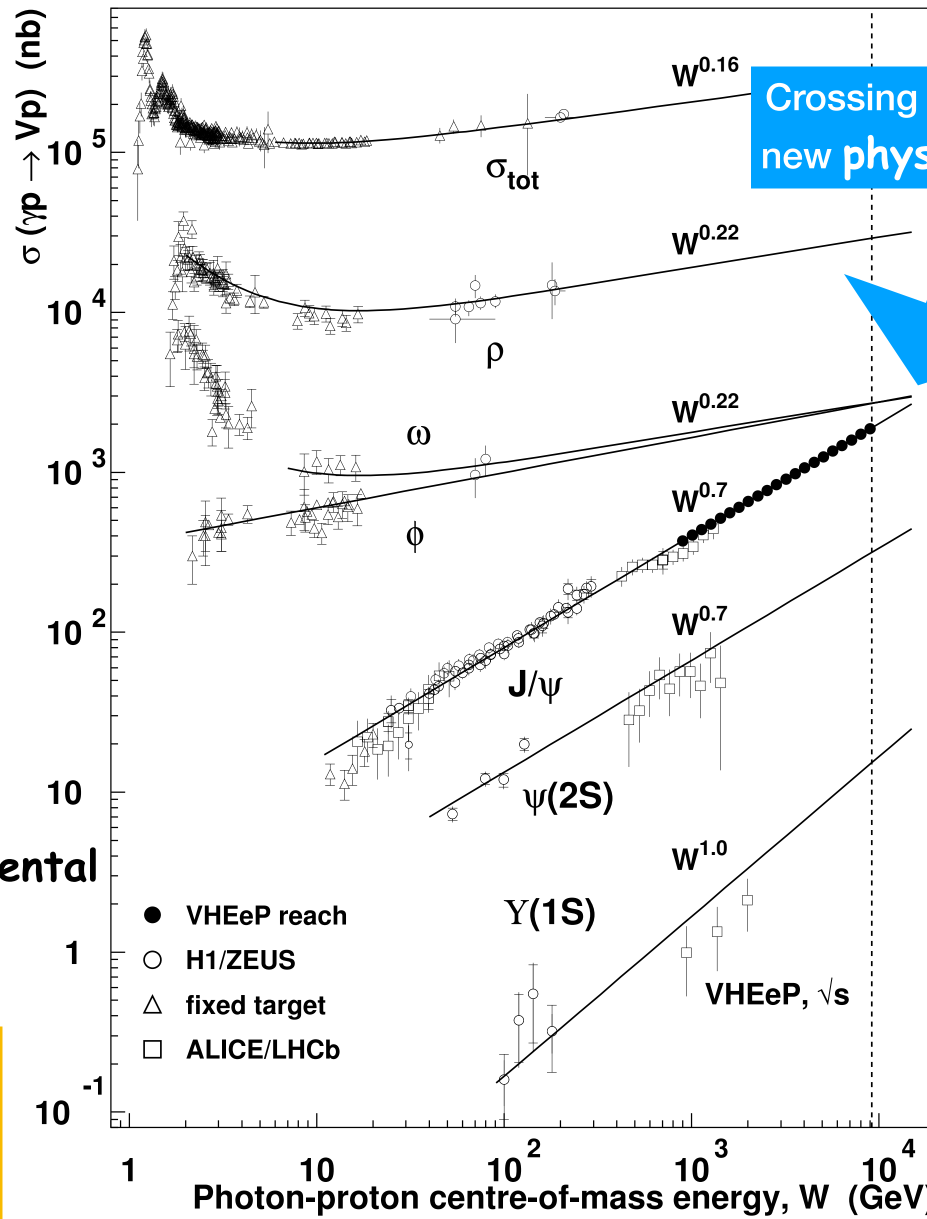
Huge cross section – no statistical uncertainty even at 10^{28} cm^{-2}s^{-1}



Virtual photon cross section: unphysical extrapolation of cross sections -> observation of saturation of parton densities ?

With the three orders of magnitude extension in the range at small-x, expect to see signs of the fundamental saturated regime.





Crossing unphysical: new **physics** needed

Exclusive processes:

Sensitive to square of gluon density

Early signs of new saturated regime

Good opportunity to see the fundamental high-energy saturated state!

eA possibility will make this physics even more dramatic "oomph"-factor again

High Energy Behavior of Cross Sections

New elementary particles or condensed matter physics?

Maybe the high-energy limit behaves differently than most expect.

UV-completion by classicalization

Gia Dvali, Gian F. Giudice, Cesar Gomez & Alex Kehagias

Journal of High Energy Physics **2011**, Article number: 108 (2011)

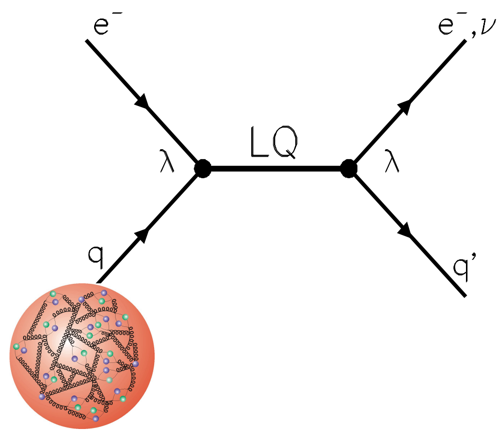
At high s, the scattering becomes dominated by production of long-lived classicalons of size $r_*(s)$, with geometric cross-section

$$\sigma \sim r_*(s)^2 \,. \tag{1.2}$$

As mandatory for classical configurations, the classicalons slowly decay into many light quanta over time-scales $t_{class} > r_* \gg 1/M_*$. The physics of such objects is entirely dominated by properties of the theory at long distances. *In the other words, classicalization converts the high-energy physics into a long distance physics.*

Good news: large cross sections!

Leptoquarks



Leptoquarks are predicted in many models for Beyond-the-Standard-Model physics. Electron-proton colliders are the ideal tool to look for this kind of process.

Fixed mass of LQ means fixed x.

$$\sigma_{\mathrm{LQ}}^{\mathrm{NWA}} = (J+1)\frac{\pi}{4s}\lambda^2 q(x_0, M_{\mathrm{LQ}}^2)$$

Spin

coupling

Sensitivity depends mostly on CM energy

Leptoquarks at the LHC

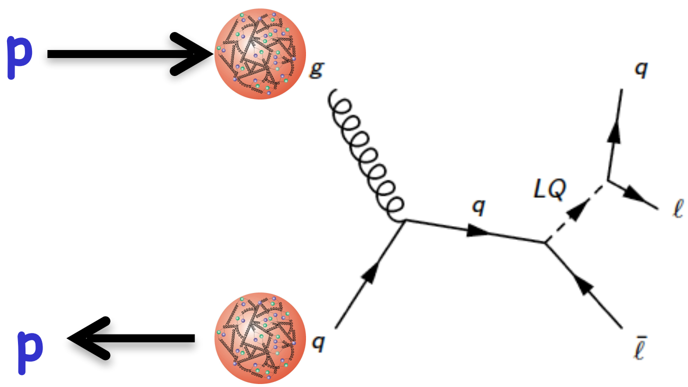


Figure 1: The s-channel resonant LQ production diagram.

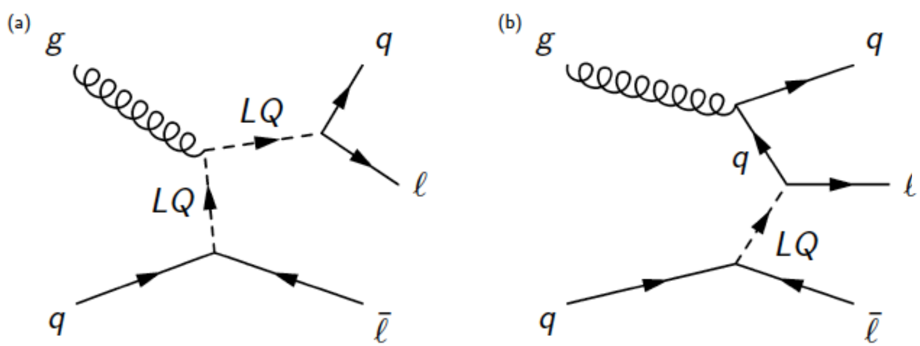
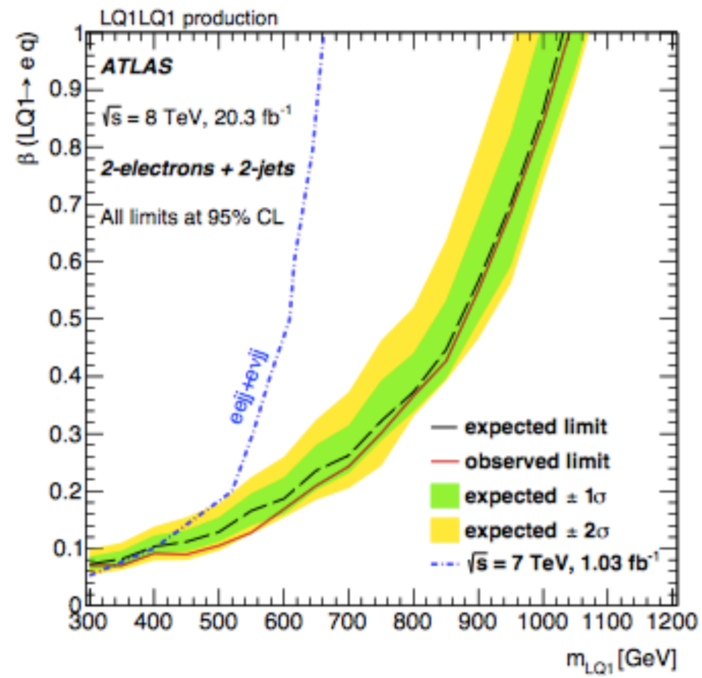
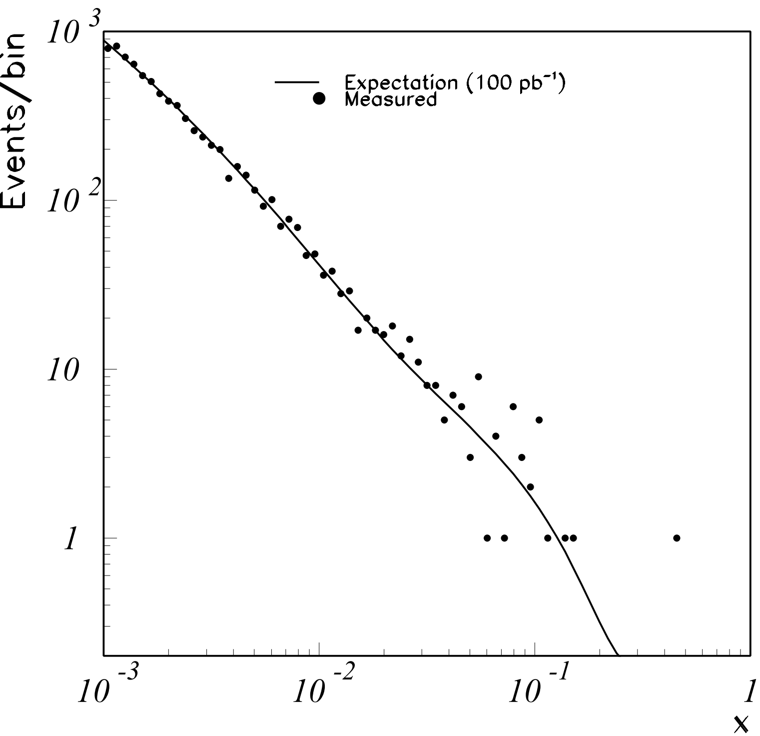


Figure 2: The t-channel LQ production diagrams with non-resonant components. The diagram



(b)

VHEeP

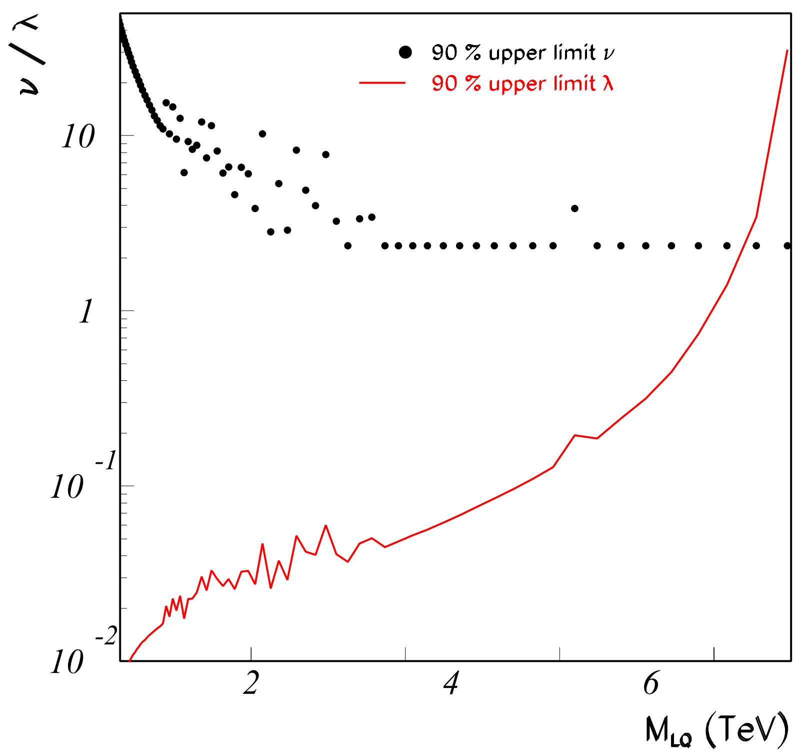


100 pb^{-1}

Require Q^2>10000 GeV^2 and y>0.1

Use Standard Model prediction (no LQ)

Sensitivity goes far beyond what is expected to be reached at LHC. (Currently ~1 TeV, later 2-3 TeV)



Conclusions-Questions

If we could provide a 5 TeV/electron bunch, with 10^{10} electrons/bunch on average 1/s - who's interested?

If we could provide 1 PeV/electrons with 10^{9}electrons/bunch on average 1/1000s - who's interested?

One option:
take what the technology can provide and explore a previously unexplored regime.